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This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1508648> since 2019-04-28T19:21:08Z

Published version:

DOI:10.1016/j.apmr.2015.02.014

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Instrumented Gait Analysis for an Objective Pre-/Postassessment of Tap Test in Normal Pressure Hydrocephalus

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<http://dx.doi.org/10.1016/j.apmr.2015.02.014>

Abstract

Objective To present an objective method to evaluate gait improvements after a tap test in idiopathic normal pressure hydrocephalus (INPH).

Design Retrospective analysis of gait data.

Setting Public tertiary care center, day hospital. The gait analysis was performed before and 2 to 4 hours after the tap test.

Participants Participants included patients with INPH (n=60) and age- and sex-matched controls (n=50; used to obtain reference intervals). From an initial referred sample of 79 patients (N=79), we excluded those unable to walk without walking aids (n=9) and those with incomplete (pre-/posttap test) gait data (n=10). Thirteen out of 60 patients were shunted and then reappraised after 6 months.

Interventions Not applicable.

Main Outcome Measures Mahalanobis distance from controls, before and after the tap test. Eleven gait parameters were combined in a single quantitative score. Walking velocity was also evaluated because it is frequently used in tap test assessment.

Results Patients were classified into 2 groups: tap test responders (n=22, 9 of them were shunted) and not suitable for shunt (n=38, 4 of them were shunted). In the tap test responders group, 9 out of 9 patients improved after shunt. In the not suitable for shunt group, 3 out of 4 patients did not improve. Gait velocity increased after the tap test in 53% of responders and in 37% of patients not suitable for shunt.

Conclusions The new method is applicable to clinical practice and allows for selecting tap test responders in an objective way, quantifying the improvements. Our results suggest that gait velocity alone is not sufficient to reliably assess tap test effects.

Keywords Hydrocephalus, normal pressure; Multivariate analysis; Rehabilitation; Spinal puncture; Ventriculoperitoneal shunt

List of abbreviations CSF, cerebrospinal fluid; INPH, idiopathic normal pressure hydrocephalus; ROM, range of motion; TT, tap test

Normal pressure hydrocephalus is a neurologic condition characterized by an enlargement of the ventricles and by a clinical picture named the Hakim triad (gait impairment, mental deterioration, urinary incontinence).^{1, 2, 3, 4, 5, 6, 7, 8 and 9} The symptoms of the disease can be improved by shunting of cerebrospinal fluid (CSF). Shunt surgery is routinely applied to selected patients after careful clinical assessment of the potential risks and benefits.¹⁰

The diagnosis relies on convergence of clinical history, physical examination, and brain imaging showing a ventricular enlargement.^{2, 4 and 8} Despite the classic clinical picture, the daily diagnosis of the disease is complicated because of the variability in its clinical presentation and course. In fact, other frequent conditions of older adults (eg, cerebrovascular disease, neurodegenerative disorders, spinal stenosis, primary urological disorders) may present similarly to idiopathic normal pressure hydrocephalus (INPH).⁴ Supplemental prognostic tests (eg, intracranial pressure monitoring, external lumbar drainage test, measurement of CSF outflow resistance, CSF tap test [TT]) have been used in clinical practice to attain a higher specificity and sensitivity for diagnosis of INPH and to achieve a reliable prediction of a positive shunt response.^{11 and 12}

Although the CSF tap is regarded as less sensitive than the external lumbar test,⁸ it is largely used because it is considered easy, safe, and inexpensive and is not a time-consuming test. A positive response of gait disturbances to a 40 to 50 mL TT is generally considered to have a high degree of certainty for a favorable response to shunt placement. The guidelines of the Japan Neurosurgical Society⁶ and European INPH Multicentre Study Group^{5, 10 and 12} point out the positive predictive value of the TT (73%–100%). Nevertheless, they suggest that a negative result of the CSF TT should not exclude patients from surgery because of the test's low sensitivity. In spite of the widespread use of the TT to determine shunt responsiveness, instrumented gait analysis is very seldom used as an outcome measure.^{13, 14, 15 and 16}

Patients with INPH frequently show a reduced gait velocity and a diminished and highly variable step length. Specific features of their gait disturbance are a broad-based gait pattern with outward rotated feet and a diminished height of the steps.¹⁵ They also show an augmented duration of the period of double support (ie, percentage of the gait cycle in which both feet are in contact with the ground).¹⁶ This feature is often referred to as magnetic gait to highlight the patient's difficulty in raising the foot from the floor during limb advancement.

Gait improvement after the TT is often evaluated by clinicians in a subjective way or by performing simple walks (eg, 10-m walk test).^{17, 18, 19, 20 and 21} Performing the 10-m walk test is the equivalent of measuring the patient's gait velocity.

Instrumented gait analysis may be an important tool to objectively assess gait changes after the TT, therefore helping clinical decision in shunt candidate selection.¹⁶ Recent advances in gait analysis highlight the importance of evaluating uninterrupted walking trials lasting 2 to 3 minutes.^{22, 23, 24, 25 and 26} This allows

for a reliable evaluation of gait parameters because 50 to 150 gait cycles are collected and analyzed for each patient.

The aim of this work is to present an objective method for selecting TT responders, based on gait parameters automatically extracted from an instrumented walk.

Methods

Participants

Seventy-nine consecutive patients diagnosed with clinical suspected INPH were referred to our gait analysis laboratory from the neurosurgery or neurology units, between 2011 and 2014, to evaluate gait improvements after a TT. The patients generally showed a short-stepped magnetic gait, cognitive disturbances, and in many cases, urinary incontinence. All patients were submitted to neuropsychological evaluation and brain magnetic resonance imaging. Patients reached our unit early in the morning and were assessed a first time by instrumented gait analysis. Then they underwent a spinal CSF tap of 30 to 50 mL in the neurosurgery unit. From 2 to 4 hours after the TT, patients' gait was assessed a second time with the same procedure.

We studied retrospectively our gait analysis database. Patients were excluded from the study when they were unable to walk without walking aids ($n=9$), when they did not complete the entire protocol (9 participants missed the post-TT evaluation), or when data were corrupted ($n=1$). Sixty patients (44 men, 16 women; mean age, 73 ± 8 y) were considered for the analysis. Thirteen of these 60 patients underwent shunt surgery. All except one were assessed a third time by gait analysis, 6 months after surgery. The remaining subject could not perform the gait test because he was not able to walk any more.

The selection of patients to be shunted was based on a clinical report summarizing the more relevant gait changes observed after the TT. The report included the subjective impressions of the team on movement fluency during gait. It also included perceived sensations of patients (or their relatives): they were interviewed by phone about gait, memory, and continence within the 24 hours after the TT.

A control group of 50 volunteers (30 men, 20 women) of similar age (mean age, 71 ± 12 y) was recruited from the local community to obtain reference intervals, in normative health conditions, for the studied gait parameters. Controls were clinically assessed prior to the gait analysis test to exclude the presence of orthopedic or neurologic disorders that could affect their gait. They performed the instrumented gait test only once.

The research reported in this article was undertaken in compliance with the ethical principles of the Declaration of Helsinki.

Experimental setup

The instrumented test was performed by an easy-to-use, inexpensive, and reliable multichannel recording system^{22, 23, 24, 25 and 26} used in clinical gait analysis. Three footswitches were fixed under the heel and the first and fifth metatarsal heads of each foot sole (fig 1A), and a knee goniometer was attached to the lateral side of each leg (fig 1B). Subjects were instructed to walk barefoot at a self-selected speed. They walked back and forth over a 9-m pathway for 2.5 minutes (fig 1C). The system recorded, for each lower limb, the foot-floor contact signal and knee flexion-extension angle (in the sagittal plane). The sampling frequency was 2kHz. The foot-floor contact signal was debounced and converted to a 4-level signal by the system software, coding the gait phases of heel contact, flat-foot contact, push off, and swing. Then, the signal was segmented into separate gait cycles as described in Agostini et al.²⁴ The knee kinematic signal was low-pass filtered (finite impulse response filter; 100 taps; cutoff frequency, 15Hz). In the analysis we considered only the walking along a linear path, discarding the strides related to direction changes. This is automatically managed by the system software. More specifically, a multivariate statistical filter (Hotelling t test, $\alpha=.05$) discarded the outlier cycles (ie, strides with abnormal timing, such as those relative to deceleration, reversing, and acceleration). A video recording of the subject's walk was also captured, synchronous with gait signals. Subject preparation and signal acquisition overall required about 15 minutes.

Fig 1. → (A) Footswitches placed under the foot sole. (B) Knee goniometer measuring the joint angle in the sagittal plane. (C) Walking path.

Gait parameters

For each foot, the system identifies the time events of the 4 gait phases (fig 2). It also calculates the double-limb support, defined as the percentage of the gait cycle in which both feet are in contact with the ground.²⁷ Furthermore, it calculates the dynamic range of motion (ROM) of the knee joint, defined as the difference between the maximum and minimum flexion-extension angle observed during the gait cycle.

Fig 2. → Schematization of gait phases (right foot). A dark circle under the foot sole indicates a closed footswitch.

Summarizing, for each subject we considered the following 11 parameters: heel contact duration (left and right), flat-foot contact duration (left and right), as a percentage of the gait cycle; push-off duration (left and right), swing duration (left and right), double-limb support duration, all expressed as a percentage of the gait cycle, and dynamic ROM (left and right), in degrees.

The gait parameter differences between patients and controls were estimated with Student t tests (2 samples; 2 tailed; level of significance, $\alpha=.05$).

Mahalanobis distance from controls and rule to select TT responders

A preliminary analysis showed that no single parameter was sufficient to describe a patient's gait, but all of them were relevant. However, because our aim was to

compare the patient's performance before and after the TT, we found it important to obtain a single indicator scoring the patient's gait, rather than analyze many parameters separately. To this purpose, we calculated the Mahalanobis distance of each patient from the group of controls,²⁸ using the 11 gait parameters previously defined. This multivariate distance describes how much a patient's performance deviates from the controls. We scored the performance of each patient before the TT, after the TT, and when the patient was operated on, after the shunt.

Then we established if a patient's gait before the TT was altered with respect to the controls. Not suitable for the TT was defined as patients with normative gait. In fact, it is reasonable to avoid the TT (and surgery) in patients within the range of normality. The upper limit of this range was defined as the controls' mean Mahalanobis distance + 3 SDs. Among patients suitable for the TT, we defined TT responders as those who decreased their Mahalanobis distance by at least 10%, after the TT, and nonresponders were defined as those who did not. To decrease the Mahalanobis distance (from controls) means getting closer to normative gait.

We used custom software routines^b to calculate the Mahalanobis distances and select the TT responders. These routines are available on request.

Gait velocity

We calculated the gait velocity before and after the TT using video recordings. We timed each patient's passage through the 9-m walkway (see fig 1C). More specifically, we measured the time that the patient needed to walk from point P to point Q, then from point Q to point P, then from point P to point Q again, and so forth, timing each passage with the exclusion of direction changes. The average velocity was defined as the total distance walked in a straight line divided by the patient's total walking time along the straight line. Similarly to what is suggested in the literature,²¹ we defined velocity improvement as an increase in the velocity, after the TT, of at least 10%.

Group matching

A Student t test (2 samples; 2 tailed; level of significance, $\alpha=.05$) was used to compare age between the INPH and control groups. A chi-square test for homogeneity of proportions was used to study sex differences between groups ($\alpha=.05$). The INPH and control groups did not show significant differences for age ($P=.35$) or sex ($P=.14$).

Sensitivity analysis

In the presented methodology based on the Mahalanobis distance, we introduced the following 2 thresholds: the limit defining the range of normality (mean + 3 SDs) and the minimum Mahalanobis distance percentage change (10%), indicating a significant improvement after the TT. The values assigned to these thresholds is

reasonable but subjective. To test the robustness of the chosen values, we performed a sensitivity analysis,²⁹ studying to what extent the results obtained depend on the chosen thresholds.

Results

The average distance that patients walked within 2.5 minutes was 80 ± 40 m, considering only the straight path. The gait parameters of the subjects included in the study are reported in table 1. Patients showed a decreased velocity, swing, and knee ROM and increased double support and flat-foot contact with respect to controls, both pre- and post-TT.

Table 1 →

Selection of TT responders using the Mahalanobis distance

We selected 41 patients suitable for the TT and 19 not suitable for the TT. Among the 41 patients suitable for the TT, 22 responded to the TT and 19 did not. Hence, overall, 38 patients were not suitable for a shunt (19 not suitable for the TT, 19 nonresponders).

In figure 3, we reported, for each patient, the Mahalanobis distance value before the TT (indicated by an asterisk) and after the TT (indicated by a triangle). We also reported the Mahalanobis distance value after the shunt (indicated by a circle), when applicable. The range of normality spans between 0 and 26 arbitrary units. The horizontal line indicates the normality upper limit. The higher the Mahalanobis distance value, the worse the patient's gait impairment. Patients suitable for the TT are those indicated by asterisks above the horizontal line. Among them, the TT responders are highlighted by a rectangle. The further the triangle from the asterisk (below it), the higher the gait improvements are, because of the CSF tap.

Fig 3. → *Pre- and post-TT Mahalanobis distance for each patient. Postshunt Mahalanobis distance is also displayed, when applicable. Rectangles indicate tap test responders; arrow, operated patients classified as not suitable for a shunt. The horizontal line delimits the range of normality. Abbreviation: a.u., arbitrary units.*

Thirteen patients underwent shunt surgery. Nine of them were in the TT responder group (patient nos. 7, 12, 14, 18, 19, 28, 39, 44, 54). Four of them were in the group not suitable for shunt (indicated by an arrow in fig 3). More specifically, of these 4 patients, 1 was in the group not suitable for the TT (patient no. 58), and 3 were in the group of nonresponders (patient nos. 3, 41, 57).

In the group of TT responders, all of the patients improved after the shunt (9 of 9 patients). Their Mahalanobis distance decreased on average from 147 ± 144 (before the TT) to 84 ± 95 arbitrary units (after the TT) and further decreased to 42 ± 40

arbitrary units after the shunt. Hence, their improvements after the shunt were on average higher than those after the TT. More specifically, the Mahalanobis distance percentage decrement was $44\% \pm 21\%$ after the TT and $59\% \pm 27\%$ after the shunt. In the group of 4 patients not suitable for a shunt, 2 worsened their condition (1 was unable to walk 6mo after the shunt), 1 did not change his condition, and 1 improved after the shunt (see the Discussion for further details). Figure 4 outlines these results.

Fig 4. → *Schematization of the study results.*

Gait velocity

Gait velocity improved in 53% of the TT responders and in 37% of patients not suitable for a shunt. More specifically, focusing on the latter, velocity improved in 29% of patients classified as not suitable for the TT and in 44% of nonresponders.

In shunted patients, on average, the velocity increased after the TT from 0.5 ± 0.3 to 0.7 ± 0.2 m/s and further increased after the shunt (0.8 ± 0.2 m/s). Among the 9 patients classified as TT responders, 3 did not improve their velocity after the TT. Among the 4 patients classified as not suitable for a shunt, 2 improved their velocity after the TT, but they did not improve after the shunt in velocity or Mahalanobis distance.

Sensitivity analysis

We varied the first threshold (defining the limit of normality) between (mean + 2.5 SDs) and (mean + 3.5 SDs). When this first threshold was set to (mean + 2.5 SDs), 3 more patients were classified as TT responders (error = $3/60 = 5\%$); however, considering (mean + 3.5 SDs), no change was obtained in the classification of TT responders (error = 0%). Varying the second threshold (minimum Mahalanobis distance percentage decrease) in the range of 5% to 15%, no change was obtained in the classification of TT responders (error = 0%). None of the aforementioned threshold variations altered the results presented for the 13 patients after the shunt (error = 0%).

Discussion

Clinicians have not reached a consensus on the usefulness and predictive value of the TT. The sensitivity and specificity reported are very variable from study to study.^{2, 5, 6, 8, 11 and 12} A major issue in establishing the prognostic value of the CSF tap is the method applied to document gait changes. The use of inadequate and/or subjective outcome measures may be a critical aspect.^{13 and 14} Furthermore, if gait improvements after the CSF tap are small, they can be missed by a clinical examination not supported by an instrumented test.¹³

We presented an objective method to score the patient's gait performance, before and after the TT, based on the measure of parameters extracted from an instrumented gait analysis lasting 2 to 3 minutes. We demonstrated that this approach is feasible in clinical practice. We are now routinely applying gait analysis for TT assessment in our center.

We hypothesized that a functional improvement may be expected only in patients with clinically appreciable gait disturbances. Hence, it is useless to perform the TT in those whose gait is already in the range of normality. Therefore, a quantitative gait assessment before the TT allows for avoidance of unnecessary CSF taps.

Of the patients, 37% responded to the TT. All the responders that were shunted (9 out of 9) improved after surgery. Among the patients who were not candidates for a shunt, only 1 of the 4 patients improved after the shunt. However, deeper examination of this patient's clinical record revealed that he underwent an unusual CSF tap of <20mL. Such a limited tap was probably not sufficient to produce a noticeable clinical change.

Literature reports that improvements after a TT seem to be positively correlated with improvements after shunt.¹² Our results confirm this finding; however, more data are needed to explore this correlation. However, the possibility to quantify improvements after the TT, objectively and accurately, may be important to prognosticate the level of improvement after surgery.

Patient's walking velocity is one of the most common measurement parameters used for evaluating TT responsiveness, and it is frequently assessed by the 10-m walk test. However, caution should be taken when considering velocity as the only parameter for describing TT responsiveness. Our results showed that velocity improved approximately in half of responders and in one third of patients who were not candidates for a shunt. This suggests that it is probably not sufficient to measure velocity for selecting shunt candidates. An explanation of this finding may be that velocity is biased by confounding factors, both in a positive or negative way. Among these factors are the habituation effect (ie, the fact that patients undergo the walking test for a second time during the day, perhaps feeling more confident and secure), fatigue effect because they are asked to fast for several hours, and pain because postlumbar puncture pain may negatively affect the gait function.²¹

Measuring a gait parameter by an automatic analysis of many strides improves the parameter's estimation accuracy.²² Furthermore, choosing multiple parameters directly correlated to gait dysfunction provides a more reliable assessment than considering a single parameter. The parameters selected for this study well represent the INPH gait dysfunctions. An increase in the double-limb support duration is directly correlated to glue-footed or magnetic gait, whereas a reduced knee flexoextension is correlated with the attitude of walking with broad-based strides of reduced length. On the other hand, we decided to discard cadence from the analysis. Cadence is defined as the number of strides per minute. We found that this parameter may be misleading for the INPH population because pre- and postchanges may be difficult to interpret in

many practical situations. As an example, cadence may increase if velocity increases (functional improvement) or step length reduces (functional worsening).

Study limitations

We did not apply this technique to patients needing mobility aids (canes, walkers). This is only a partial limitation because some of the patients using walking aids before the TT were able to walk without them after the TT. In these cases, clinical improvement was evident without the need for an instrumented gait analysis.

Among the 22 responders, only 9 were shunted. The remaining 13 patients were not operated on because of serious comorbidities (lung cancer, hepatocellular carcinoma, severe cardiomyopathy) or because they asked to procrastinate the intervention to a later date.

Conclusions

We proposed a new method to evaluate the effects of the CSF lumbar tap on gait. The method is promising both in terms of objectiveness and reliability. This approach is based on the use of many gait parameters specifically studied to describe INPH walking features, summarized in a single indicator (ie, Mahalanobis distance of a single patient from the control group). Furthermore, our findings suggest that gait velocity alone may not be sufficient to establish responsiveness to the TT. Therefore, simple tests (eg, 10-m walk test) may not be sufficiently reliable as an outcome evaluation of the CSF tap and may be the cause of the actual limited predictive value of the TT.

Suppliers

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b. MATLAB; MathWorks.

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Figure 1

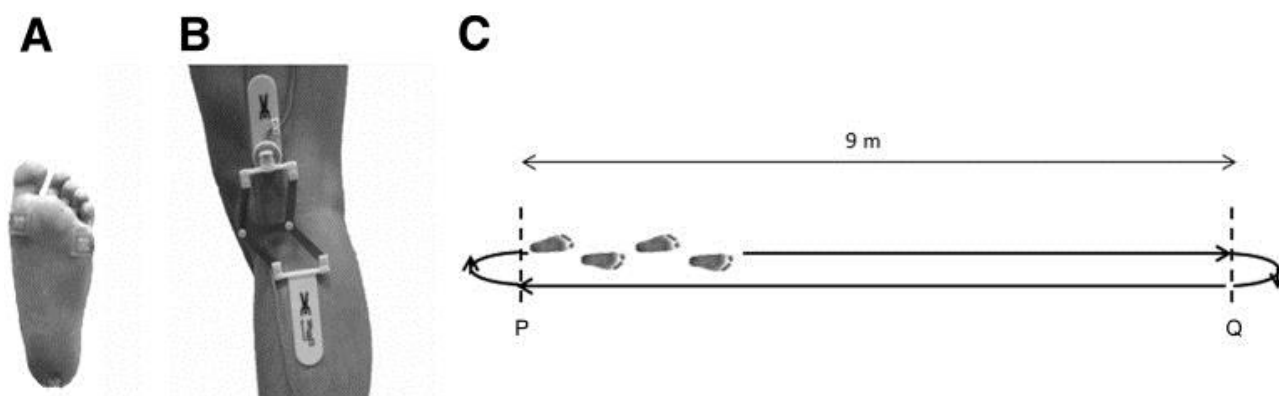


Figure 2

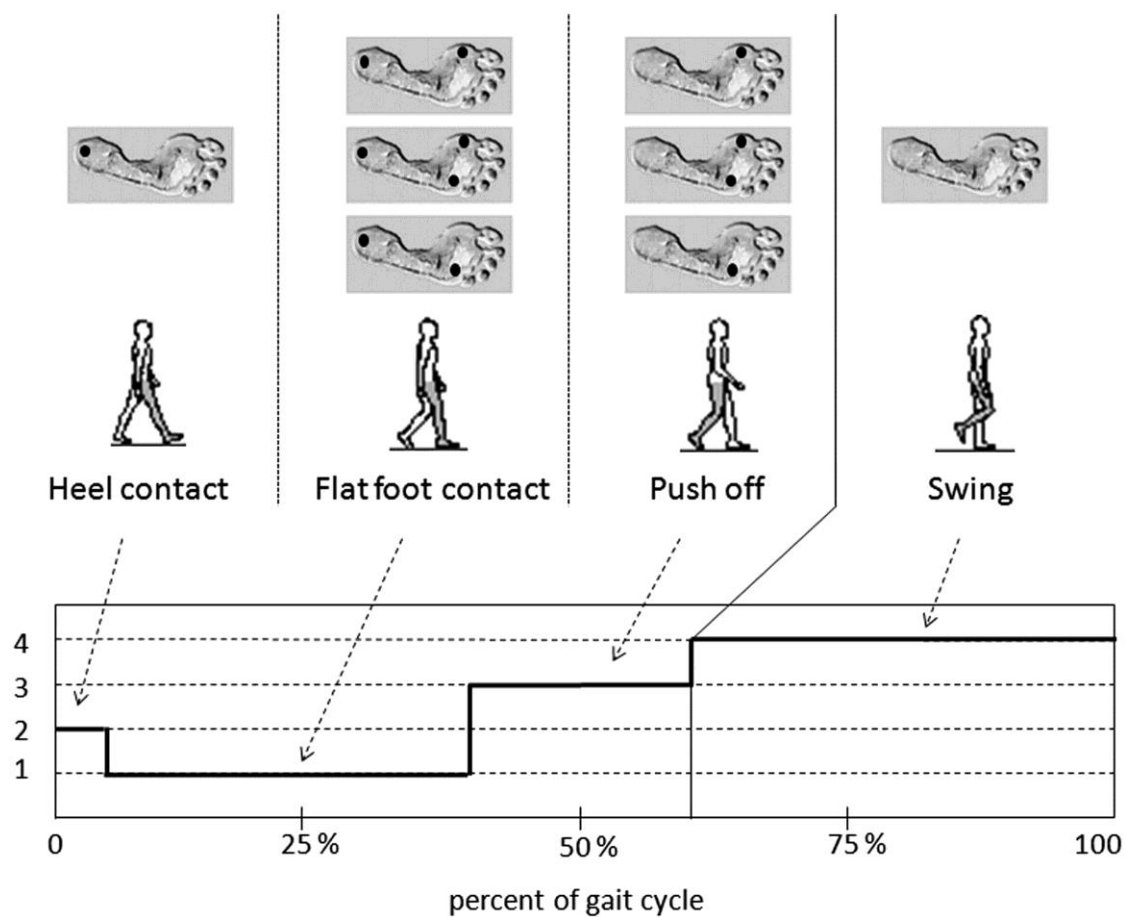


Figure 3

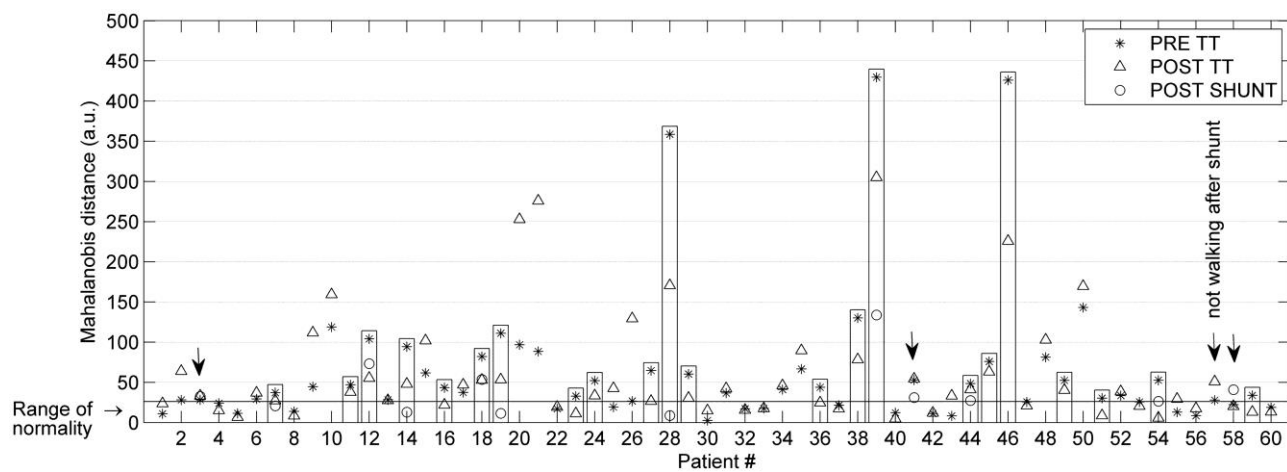


Figure 4

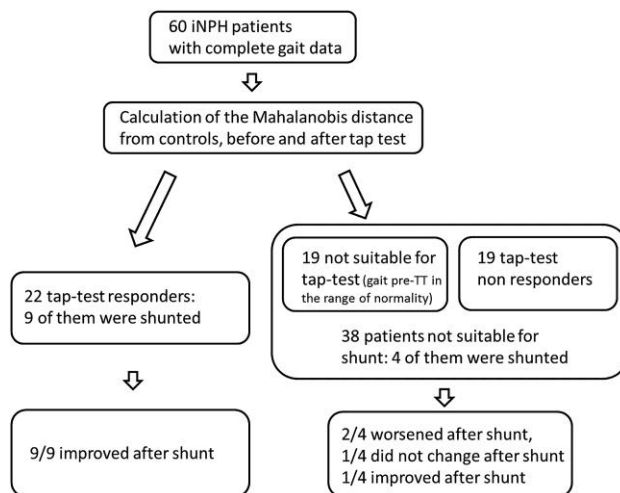


Table 1.

Gait parameters for patients with INPH and controls
Gait Parameters

	Patients With INPH (n=60)		Controls (n=50)
	Pre-TT	Post-TT	
Velocity (m/s)	0.6±0.2*	0.7±0.2*	1.0±0.1
Double support (% gait cycle)	30.9±9.7*	27.8±7.8*	17.6±4.4
Heel contact<comma> left (% gait cycle)	7.1±4.6	7.0±4.8	6.0±2.8
Heel contact<comma> right (% gait cycle)	7.3±7.0	8.3±6.9†	5.6±2.3
Flat-foot contact<comma> left (% gait cycle)	40.9±10.0*	39.6±8.8*	33.5±5.7
Flat-foot contact<comma> right (% gait cycle)	40.5±11.0*	37.4±9.0†	33.6±6.0
Push off<comma> left (% gait cycle)	17.8±6.8	17.8±6.3	19.5±3.8
Push off<comma> right (% gait cycle)	17.6±6.3	17.9±6.9	19.4±4.7
Swing<comma> left (% gait cycle)	34.1±5.1*	35.6±4.6*	41.0±2.4
Swing<comma> right (% gait cycle)	34.6±5.4*	36.3±4.3*	41.3±2.7
Knee ROM<comma> left (deg)	34.3±7.8*	34.7±7.4*	45.9±8.1
Knee ROM<comma> right (deg)	36.5±8.7*	37.4±7.6*	44.3±8.8

NOTE. Values are mean ± SD.

*

Significant differences between patients with INPH and controls are indicated with P<.001.

†

Significant differences between patients with INPH and controls are indicated with P<.05.